Error Bounds for MODIS Retrievals of the Optical Depth of Horizontally Inhomogeneous Clouds

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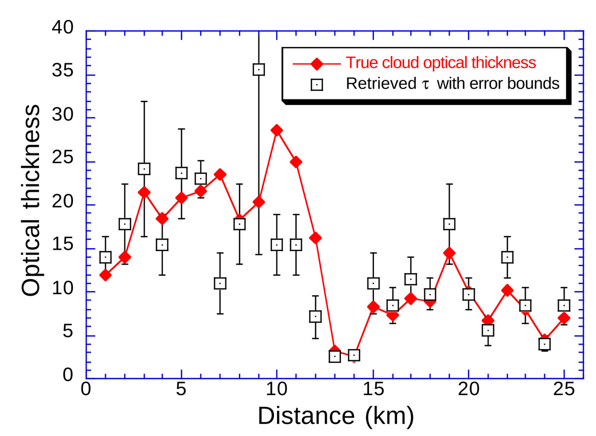
Introduction

An important product of the operational MODIS data processing is cloud optical thickness (τ). The operational procedures retrieve τ values using 1D radiative transfer theory.

The goals of our project are to:

- Examine how 3D radiative effects influence the retrievals' accuracy, and
- Develop a technique to estimate the resulting retrieval uncertainties for various cloud types.

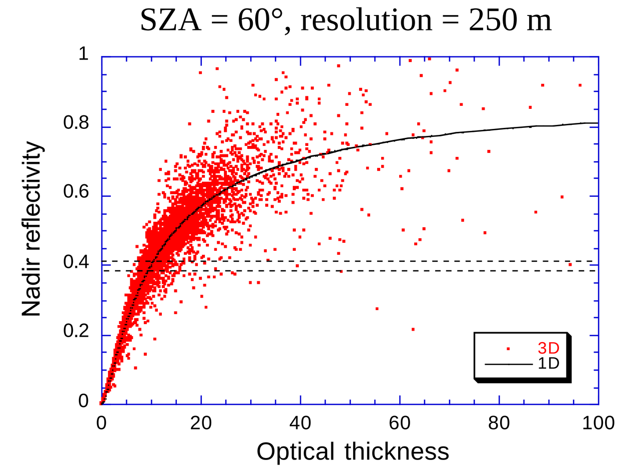
An example for retrieval uncertainties estimated through theoretical considerations, for 60° solar zenith angle (*SZA*) and 1 km resolution:



A Theoretical Approach to Evaluating Uncertainties in τ Retrievals

Step 1: Perform 3D radiative transfer simulations over a wide variety of simulated cloud fields and create a τ vs. nadir reflectivity (I) plot:

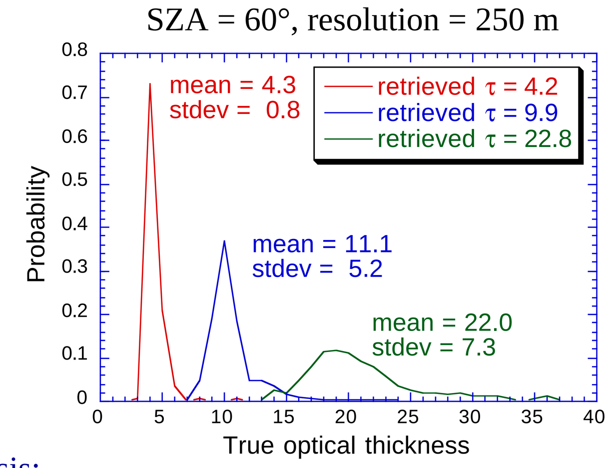
SZA = 60°, resolution = 250 m



Step 2: Take a narrow interval around a given I value (between the dashed lines) and evaluate retrieval errors by comparing the τ values retrieved using 1D theory (black curve) to the distribution of true τ values (red dots) in this interval.

Results

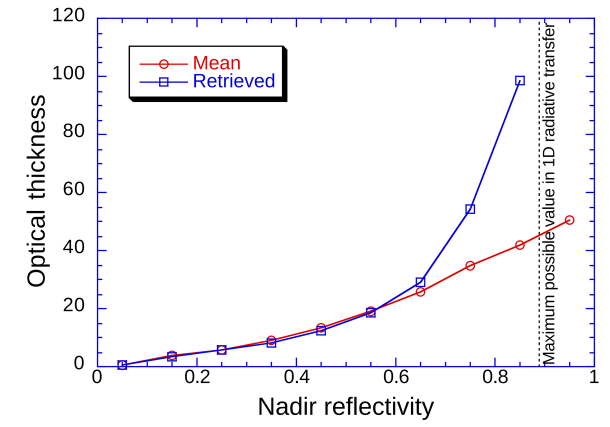
Histograms of true optical thicknesses for marine Stratocumulus
SZA = 60°, resolution = 250 m



Analysis:

- The spread of true optical thicknesses is wider for the brighter areas where retrievals estimate large optical thicknesses. This implies that retrieval uncertainties increase with retrieved optical thickness.
- The distribution is skewed, indicating that while underestimations due to shadowing can be large for any brightness, overestimations on illuminated cloud sides cannot be very large in thin areas.

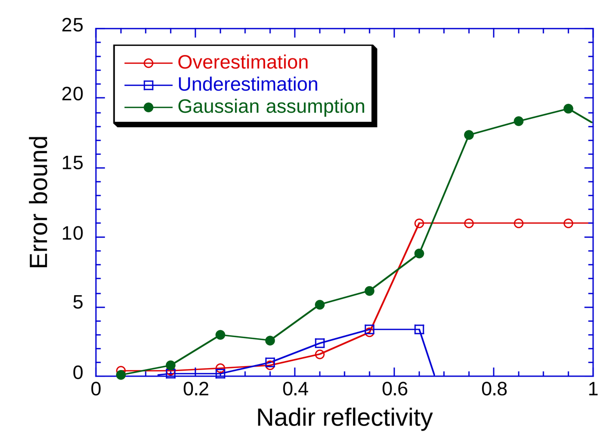
Comparison of the retrieved optical thickness to the mean of true τ values. SZA = 60°, resolution = 250 m



Analysis:

- Retrievals are unbiased for $I < 0.6$
- Retrievals overestimate mean τ for $I > 0.6$

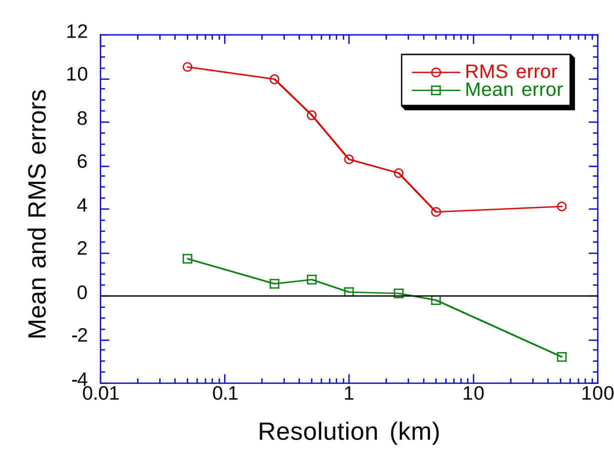
Empirical error bounds for 68% confidence level (= one standard deviation) for typical Sc clouds. SZA = 60°, resolution = 250 m



Analysis:

- Errors increase with cloud brightness.
- Due to the skewness of the error distribution, error bounds can be asymmetric.

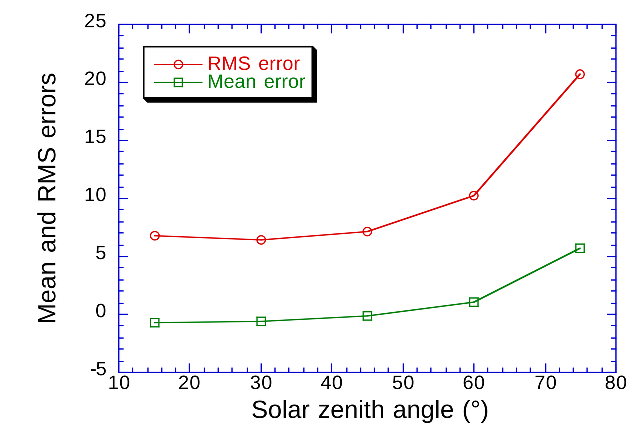
Effects of spatial resolution of retrievals for SZA = 60°



Analysis:

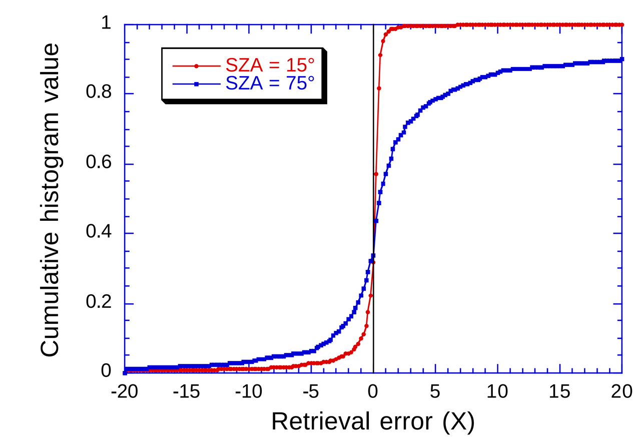
- At too high a resolution, retrievals overestimate the average optical thickness, whereas at too coarse a resolution, they underestimate it.
- Retrieval errors for individual pixels lie in a narrower range for coarser resolutions.

Effects of solar elevation at 250 m resolution



Analysis:
Errors increase with solar zenith angle

Cumulative histogram of retrieval errors
Probability (P) for individual pixel errors (E): $P(E < X)$



Analysis:

- Large underestimations are more frequent for high sun.
- Large overestimations are more frequent for oblique sun.

Summary

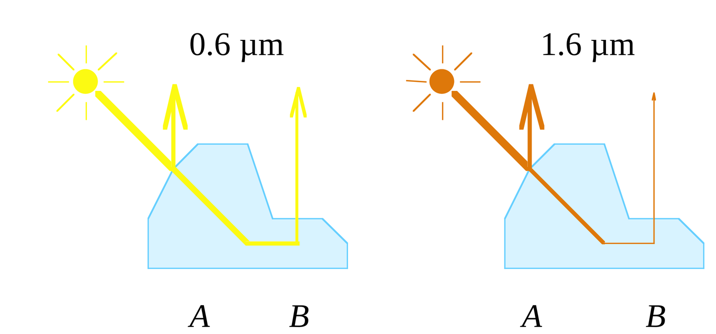
- Presented a simple theoretical approach to estimating the uncertainties that horizontal cloud variability introduces into MODIS cloud optical depth retrievals. By providing quantitative estimates of retrieval errors though error bounds, the technique can be used in the validation of operational MODIS products.
- Found that retrieval errors have a skewed probability distribution, so optimal error bounds are asymmetric. (For high sun, large underestimations are more likely, whereas for oblique sun, large overestimations are more frequent.)

Work in Progress

- Make statistics of retrieval errors climatologically representative by assigning each scene a weight that indicates how often clouds similar to the simulated ones occur in reality. The weights will be obtained by comparing the simulated scenes to cloud radar measurements.
- Improve the technique so that it estimates retrieval uncertainties based not only on overall statistics of clouds, but also on individual scene characteristics, such as the wavelength dependence and spatial variability of cloud reflection.

A Promising Approach for Oblique Sun

The approach detects 3D effects by using the fact that when 3D effects such as shadowing and horizontal diffusion are present, cloud absorption enhances the variability of near-infrared images. For example:

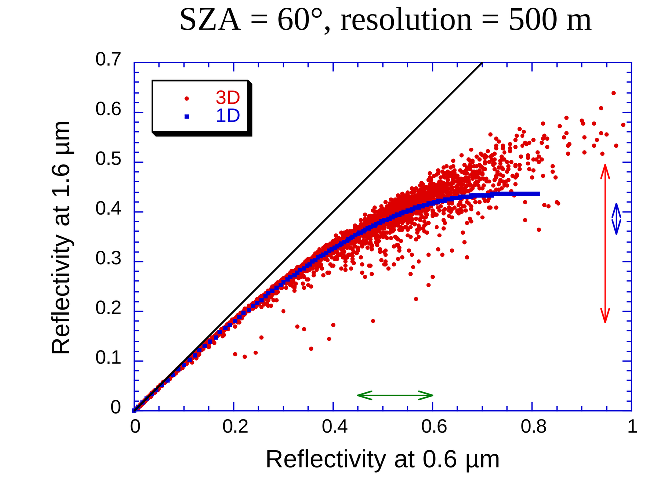


Due to diffusion, the variability (I_A - I_B) is small

Absorption reduces diffusion, so the variability (I_A - I_B) is large

The enhancement in variability is apparent on the following figure: for a given range of variability at 0.6 µm (green arrow) , there is a larger variability at 1.6 µm in 3D (red arrow) than in 1D (blue arrow) radiative transfer.

SZA = 60°, resolution = 500 m



The enhancement in variability can be calculated for (5 km)^2 areas through the following steps:

1. Get effective single scattering albedo for 1.6 µm using 1D theory and the area-averaged reflectivities at 0.6 µm and 1.6 µm.
2. Based on the variability measured at 0.6 µm, estimate the variability expected for 1.6 µm in 1D radiative transfer theory (using the effective single scattering albedo from Step 1).
3. Compare the variability measured at 1.6 µm to the expected value obtained in Step 2. Their difference is the enhancement that can be used to estimate the magnitude of 3D effects.

Preliminary results for SZA = 60° and resolution = 500 m